Flow and Regime Dependent Mesoscale Predictability

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LONG-TERM GOALS

The ultimate goals of the proposed work are to estimate the predictability of mesoscale features embedded within different synoptic-scale flow regimes and to identify key physical processes that control the limit of predictability at the mesoscale through explicit simulations of idealized moist baroclinic waves and case studies of high-impact weather events.

OBJECTIVES

Major objectives of this research include: (1) determine key dynamical differences in the flows that lead to different mesoscale error growth dynamics in different high-impact weather events; (2) generalize results of flow-dependent mesoscale predictability concluded from real case studies through explicit simulations of idealized moist baroclinic waves; (3) explore differences between warm-season and cold-season error-growth dynamics; and (4) synthesize flow-dependent mesoscale error growth dynamics with conceptual models.

Our working hypothesis, a multistage conceptual model, is that moist processes impose fundamental limits on mesoscale predictability but the error-growth dynamics is strongly dependent on the larger-scale background flow and its attendant dynamics.

APPROACH

Since the beginning of the project, three graduate research assistants (Andrew Odins, Dan Hawblitzel and Jason Sippel) and a postdoctoral research associate (Dr. Naifang Bei) have been fully or partially trained/sponsored by this project. Odins completed and defended successfully his master's thesis in the fall of 2004 on the mesoscale predictability of an extreme warm-season south-central Texas flooding event of June-July 2003 (Odins 2004; Zhang et al. 2005). Hawblitzel completed and defended successfully his master's thesis on the impact of moist convection on the predictability of a long-lived mesoscale convective event of 10-13 June 2003 (Hawblitzel 2005; Hawblitzel et al. 2006). Sippel started his Ph.D. study in January 2005 and is working on the short-term predictability of tropical cyclones using ensemble forecasts, especially formed near the coastal areas of the United States and Western Pacific Regions.

Dr. Bei has been working on several areas of the project including (1) mesoscale predictability of the Storm of the Century of March 1993 ("SOC") and its comparison to another well-studied cold-season event, the 'surprise' snowstorm of January 2000; (2) mesoscale predictability of warm-season torrential rainfall events along the Meiyu fronts in China; and (3) mesoscale predictability of idealized

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14. ABSTRACT
The ultimate goals of the proposed work are to estimate the predictability of mesoscale features embedded within different synoptic-scale flow regimes and to identify key physical processes that control the limit of predictability at the mesoscale through explicit simulations of idealized moist baroclinic waves and case studies of high-impact weather events.

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moist baroclinic waves with high-resolution simulations and diagnosis which contributes significantly to the synthesis of conceptual mesoscale error growth model.

The PI, Dr. Fuqing Zhang, has been actively working on and coordinating all aspects of the project. We have also collaborated closely with Drs. Zhe-Min Tan (Nanjing University), Craig Epifanio (Texas A&M), Chris Snyder (NCAR) and Rich Rotunno (NCAR) on idealized simulations and predictability of moist baroclinic waves as well as with Drs. Chris Davis (NCAR) and John Nielsen-Gammon (Texas A&M) on the warm-season predictability of high-impact events.

For the first objective in examining the mesoscale predictability of the “SOC” and its comparison to the “surprise” snowstorm, we performed experiments identical to those in Zhang et al. (2003). We also examine sensitivity for both cases by introducing perturbations at different stages of the cyclogenesis.

The MM5-based procedure developed in Tan et al. (2004) is used to create balanced initial conditions for simulating idealized moist baroclinic waves. This procedure includes using 3-dimensional potential vorticity (PV) inversion technique to invert the balanced finite amplitude baroclinic waves from specification of the background 3-D PV field. We further extended the low-resolution results from Tan et al. (2004) to convective-resolving simulations.

To further explain the difference of error growth found between the two observed cases and to explore factors other than moist convection and background baroclinicity in limiting mesoscale predictability in a controlled environment, we will extend our idealized predictability study of Tan et al. (2004) through explicit simulations of moist baroclinic waves by (1) introducing surface/boundary layer inhomogeneities, (2) adding perturbations at difference phase of the cyclogenesis, (3) adding background barotropic shear to the initial baroclinic jet, and/or (4) constructing more realistic configurations with different initial baroclinic and static stabilities.

For the warm-season Texas flooding event of 2002 (Nielse-Gammon et al. 2005; Zhang et al. 2006), we performed high-resolution sensitivity experiments initialized at two different times per day. Little changes in the synoptic flows through the 8-day event allow us to examine/generalize the role of CAPE variation, diurnal cycle and cold pool dynamics in modulating and limiting short-range mesoscale predictability of such an extreme warm-season flooding event.

We also extend the study of mesoscale predictability into tropical cyclones focusing on several recent events: Tropical Storm Allison (2001), “would-be” Alex (2004), Hurricanes Katrina (2005) and Humberto (2007) and Typhoon Bilis (2006). Through ensemble simulations and sensitivity experiments, we aim to examine the flow- and regime- dependent predictability of tropical cyclones.

We examined both the intrinsic and practical aspects of mesoscale predictability in which realistic and/or small amplitude errors in both the forecast model and initial conditions are considered. Four forms of idealized initial perturbations as a function of initial spatial scales are tested: (1) a monochromatic small-scale wave as in Zhang et al. (2003); (2) “grid-point” random noises with energy equally projected to all scales as in Tan et al. (2004); (3) large-scale random but balanced initial errors through inversion of the randomly-perturbed geostrophic streamfunction in the WRF/MM5 3Dvar system (Barker et al. 2003); and (4) ensemble perturbation generation through an ensemble-based mesoscale data assimilation system (Zhang et al. 2006a).

For quantitative evaluation of error evolution, we continue to use the diagnostics developed and implemented in our previous studies (Zhang et al. 2002, 2003; Tan et al. 2004) which include tracking difference energy growth between forecasts and performing spectral analysis of the difference energy.

WORK COMPLETED

We continue to make significant progress in each of the four major objectives we proposed during the past year. We have completed all the proposed model simulations and sensitivity experiments for both real-case studies and idealized moist baroclinic waves. We begin to make significant progress in the predictability of tropical cyclones, warm-season MCVs, and heavy precipitation along the meiyu front of East Asia. We also examined the impact of uncertainty on the public response to hurricane forecasts.

We also applied the advanced diagnostic tools including two-dimensional spectral decomposition and difference error energy budget analysis that we developed to quantify error growth and scale interactions more accurately. These advanced diagnostic tools greatly enhanced our conceptual understanding of error growth characteristics under the influence of moist convection.

RESULTS

There are a total of **16** journal publications directly sponsored by this project including **12** in print or in press (Tan et al. 2004; Zhang 2005; Nielsen-Gammon, Zhang et al. 2005; Zhang et al. 2006a; Zhang et al. 2006b; Hawblitzel, Zhang, et al. 2007a; Meng and Zhang 2007; Bei and Zhang 2007; Zhang et al. 2007b; Zhang et al. 2007c; Meng and Zhang 2007b) and **4** in different stages of the peer-review process (Zhang 2007; Sippel and Zhang 2007; Meng and Zhang 2007c; Morss and Zhang 2007). Highlights of the work completed during the past year are listed below:

***(1) Mesoscale predictability of tropical cyclones and hurricanes (Zhang 2007; Sippel and Zhang 2007)*:** Probabilistic methods developed in Hawblitzel et al. (2006) are used to investigate the genesis dynamics and predictability of Tropical Storm Allison (2001), a null case in which the MM5 predicted a tropical cyclone that never formed in late July 2004 and Typhoon Bilis (2006) in the Western Pacific. Allison was a weak June 2001 tropical storm best known for the copious rains and flooding it produced in southeast Texas and Louisiana. In the null case, the MM5 developed a hurricane in the Gulf of Mexico from a disturbance that was located near the Florida Keys at the model start time. In both cases, ensemble forecasts generated with the method of Barker et al (2004) are used to probabilistically evaluate the predictability and dynamics. The ensemble mean and spread and the correlation between different forecast variables at different times are investigated. An overwhelming result of both cases is that a deterministic forecast system would have absolutely not been appropriate, and even probabilistic forecasting would have had significant hurdles in these situations. For example, in the Allison case the possible track envelope predicted by the ensemble members varies depending on many factors, including the initial analysis type and grid spacing. The typical track of an ensemble member started with the GCIP initial conditions is generally west of members of the FNL ensemble. Furthermore, members of the 9 km FNL ensemble exhibit difficulty in forming a closed low over the ocean, and even when a low does form, it generally has different structure than and tracks significantly east of the low in corresponding members of the 30 km ensemble (that have used the same initial conditions). In a more extreme example, when the 2004 null case ensemble is integrated for 72 hours starting with the FNL analysis, the resulting system strength ranges from a minimal tropical storm to a strong hurricane and the location spread is from the western Gulf of Mexico to near Tampa. The genesis dynamics seem to be somewhat different, at least in terms of the ensembles, for these two cases. The three most

influential factors for the strength of Allison in the 30 km FNL ensemble were water vapor, potential vorticity, and meridional winds at 850 hPa. Ongoing work also explores the predictability of Typhoon Bilis (2006), Hurricanes Katrina (2005) and Humberto (2007) in which ensemble-based data assimilation is found significantly improve the track prediction and to reveal significant uncertainty in intensity forecast.

(2) Mesoscale predictability of moist baroclinic waves: Cloud-resolving experiments and multistage error growth dynamics (Zhang et al. 2007b): A recent study examined the predictability of an idealized baroclinic wave amplifying in a conditionally unstable atmosphere through numerical simulations with parameterized moist convection. It was demonstrated that with the effect of moisture included, the error starting from small random noise is characterized by upscale growth in the short-term (0-36 h) forecast of a growing synoptic-scale disturbance. The current study seeks to explore further the mesoscale error-growth dynamics in idealized moist baroclinic waves through convection-permitting experiments with model grid increments down to 3.3 km. These experiments suggest the following three-stage error-growth model: In the initial stage, the errors grow from small-scale convective instability and then quickly [*O(1 h)*] saturate at the convective scales. In the second stage, the character of the errors changes from that of convective-scale unbalanced motions to one more closely related to large-scale balanced motions. That is, some of the error from convective scales is retained in the balanced motions, while the rest is radiated away in the form of gravity waves. In the final stage, the large-scale (balanced) components of the errors grow with the background baroclinic instability. Through examination of the error-energy budget, it is found that buoyancy production due mostly to moist convection is comparable to shear production (nonlinear velocity advection). It is found that turning off latent heating not only dramatically decreases buoyancy production, but also reduces shear production to less than 20% of its original amplitude.

(3) Probabilistic Evaluation of the Dynamics and Predictability of the Mesoscale Convective Vortex of 10-13 June 2003 (Hawblitzel et al. 2007): This study examines the dynamics and predictability of the mesoscale convective vortex (MCV) of 10-13 June 2003 through ensemble forecasting. The MCV of interest developed from a preexisting upper-level disturbance over the southwest United States on 10 June and matured as it traveled northeastward. This event is of particular interest given the anomalously strong and long-lived nature of the circulation. An ensemble of 20 forecasts using a two-way nested mesoscale model with horizontal grid increments of 30 and 10 km are employed to probabilistically evaluate the dynamics and predictability of the MCV. Ensemble mean and spread as well as correlations between different forecast variables at different forecast times are examined. It is shown that small-amplitude large-scale balanced initial perturbations may result in very large ensemble spread, with individual solutions ranging from a very strong MCV to no MCV at all. Despite similar synoptic-scale conditions, the ensemble MCV forecasts vary greatly depending on intensity and coverage of simulated convection, illustrating the critical role of convection in the development and evolution of this MCV. Correlation analyses reveal the importance of a preexisting disturbance to the eventual development of the MCV. It is also found that convection near the center of the MCV the day after its formation may be an important factor in determining the eventual growth of a surface vortex, and that a stronger mid-level vortex is more conducive to convection, especially on the downshear side, consistent with findings of previous MCV studies.

(4) Mesoscale predictability of a warm-season torrential rainfall event along the Mei-yu front of China (Bei and Zhang 2007): Summertime heavy precipitation associated with the quasi-stationary Mei-Yu front often causes severe flooding in China. This study explores the mesoscale predictability of one such event. The 20-21 July rainfall event contributed to making the 1998 flood season the worst

in this region since 1954. Various sensitivity experiments are performed to examine the impact of both realistic and idealized initial condition uncertainties of different scales and amplitudes on the prediction of the mesoscale precipitation systems along the Mei-Yu front. While it is found that mesoscale model simulations initialized with global analyses at a 36-h lead time can reasonably well depict the evolution of the synoptic environment, there are large variations between different experiments in the prediction of the mesoscale details and heavy precipitation of this event. It is also found that larger-scale, larger-amplitude initial uncertainties generally lead to larger forecast divergence than do uncertainties of smaller scales and small amplitudes. However, the forecast errors induced by perturbations of the same amplitude but at different scales are very similar if the initial error is sufficiently small. Error growth is strongly nonlinear and small-amplitude initial errors, which are far smaller than those of current observational networks, may grow rapidly and quickly saturate at smaller scales. They subsequently grow upscale, leading to significant forecast uncertainties at increasingly larger scales. In agreement with previous studies, moist convection is found to be the key to the rapid error growth leading to limited predictability at the mesoscales. These findings further suggest that, while there is significant room for improving forecast skill by improving forecast models and initial conditions, predictability of heavy precipitation at the mesoscales is inherently limited.

(5) Public response to Hurricane forecast uncertainty along the Texas Coast (Zhang et al. 2007; Morss and Zhang 2007): Hurricane Rita made landfall near the Texas-Louisiana border in September 2005, causing major damage and disruption. As Rita approached the Gulf Coast, uncertainties in the track and intensity forecasts of Rita, combined with the aftermath of Hurricane Katrina, led to major evacuations along the Texas coast and significant traffic jams in the broader Houston area. In the spring semester of 2006, a student research project at Texas A&M University were developed to investigate the societal impacts of Hurricane Rita and its forecasts in greater depth. Through in-person interviews in the Texas Gulf Coast cities of Galveston, Port Arthur, and Houston, it is found that the vast majority of respondents evacuated from Hurricane Rita, and more than half stated that Hurricane Katrina affected their evacuation decision. Despite the major traffic jams and the minimal damage in many evacuated regions, most evacuees interviewed do not regret their decision to evacuate. The majority of respondents stated that they intend to evacuate for a future Category 3 hurricane, but the majority would stay for a Category 2 hurricane. Despite the forecast uncertainties, the respondents had high confidence in the forecasts of Rita provided by the National Hurricane Center.

IMPACT/APPLICATIONS

Understanding of the limit of mesoscale predictability and the associated error growth dynamics is essential for setting up expectations and priorities for advancing deterministic mesoscale forecasting and for providing guidance on the design, implementation and application of short-range ensemble prediction systems. Understanding the nature of mesoscale predictability is also crucial to the design of the efficient data assimilation systems for the meso- and regional scales. The advanced ensemble-based data assimilation system which is capable of assimilating both ground and airborne Doppler radar observations is very promising for the future cloud-resolving mesoscale prediction, especially so for tropical cyclones including typhoons and hurricanes.

TRANSITIONS

In collaborations with scientists at NRL Monterey, the WRF-based ensemble data assimilation system partially sponsored by this project is currently being transplanted to the Navy mesoscale prediction model COAMPS with the potential to be used in future operational forecasts.

RELATED PROJECTS

Collaborative Research: Ensemble-based State Estimation for Weather Research and Forecast Model. National Science Foundation (NSF); 09/01/02-08/31/08; $295,000; Fuqing Zhang (Principal Investigator). The NSF sponsored project closely related to this project because mesoscale predictability and data assimilation are two integral parts of state estimation. Data assimilation provides better initial condition to assess predictability while predictability points to the ultimate benefits and limitations of data assimilation.

Dynamics and Impacts of Mesoscale Gravity Waves. National Science Foundation (NSF); 09/15/02-02/28/07; $224,834; Fuqing Zhang (Principal Investigator) and "Dynamics and Impacts of Mesoscale Gravity Waves from Baroclinic Jet-Front Systems". National Science Foundation (NSF); 11/01/06-10/31/09; $399,961; Fuqing Zhang (Principal Investigator). Both NSF sponsored projects are closely related to this project because gravity wave dynamics and geostrophic adjustment play an important role in understanding the upscale growth of error energy from moist convection which limits to limit of mesoscale predictability.

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